A relationship between atmospheric rain reflectivity and elevation variance due to drop impact on the sea surface

C. Craeye, P. Sobieski,
Université catholique de Louvain
Place du Levant, 2,
B- 1348 Louvain-la-Neuve, Belgium
craeye@tele.ucl.ac.be, sobieski@tele.ucl.ac.be

L.F. Bliven,
NASA- Wallops Flight Facility,
Wallops Island, VA 23337, USA
Francis.L.Bliven@nasa.gov

Abstract- **The additional surface roughness created by drops impacting the sea surface can bias wind speed estimates obtained from satellite scatterometric measurements. The additional roughness essentially depends on the rain content in very large drops. The estimate of this contribution will be highly dependent on the model chosen for the drop size distribution. However, it has been observed that the reflectivity of the drops falling in the atmosphere has a drop-size dependence that is very similar to that of the surface roughness induced by rain. This paper shows how reflectivity data can be used to improve the estimate of the elevation variance resulting from drop impact.**

I. INTRODUCTION

The impact of raindrops on the sea surface can significantly modify its reflectivity. This can introduce a bias in the wind speed estimations based on scatterometric or radiometric measurements. Moreover, as explained by Meneghini et al [9,10], rain rate retrieval algorithms generally also rely on the estimation of the surface reflectivity. The latter is often considered equal to the reflectivity just outside the rain cell, which does not account for the effects of drop impact and could introduce a corruption of the estimated rain attenuation appearing in retrieval algorithms [5].

As a first step, we assume that the impact of drops on the sea surface yields an additional component in the surface elevation spectrum, superimposed to the surface spectrum due to instantaneous wind speed and wind history. In order to quantify this effect, laboratory experiments were carried out by Bliven and Sobieski [1,2,11,12]. Those yield the roughness appearing on a water surface subject to artificial rain, along with corresponding radar backscattering signatures. The two spectra are represented in Fig. 1 for increasing wind friction velocities (u*) and rain rates R. The wind spectrum is obtained here from the model of Bjerkaas and Riedel (1979) but could be replaced by any other one [8].

Two-scale electromagnetic scattering models were then used to quantify the effect of rain on the surface reflectivity change. In some configurations, it has been found that the surface radar reflectivity due to rain could change by up to 10 dB [3].

II. SURFACE ELEVATION SPECTRUM

The wave tank experiments, associated with scattering simulations, were performed initially for mono-disperse artificial rain events, only made of drops with diameters equal to 2.8 mm. However, natural rain being far from mono-disperse, further experiments to analyze the drop-size dependence were conducted [7].
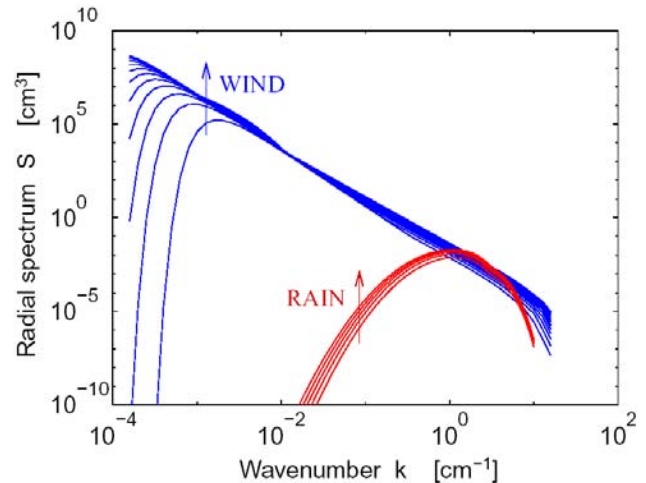

Fig.1: Radial sea surface elevation spectrum S(k) for increasing wind friction velocities u* and rain rate R. u* ranges from 20 to 120 cm/s by steps of 10 cm/s and R ranges from 20 to 100 mm/hr by steps of 20 mm/hr.

From those new experiments, it appeared that the largest drops have a much larger contribution to the surface elevation variance than small ones. This was consistent with single-drop experiments performed by Craeye et al. [4], who found that the energy transferred by the drop into surface waves is not simply proportional to the kinetic energy of the drop.

Indeed, the larger the drop, the larger the relative contribution to the surface energy. Actually, it appeared that the contribution of a given drop to the surface elevation variance is practically proportional to its squared momentum $m^2 v^2$. This simple rule seems to be consistent with the experimental data analyzed for various mono-

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disperse rain events, as reported in [7]. Figs. 3 and 4 illustrate the quality of the scaling rule based on the square-momentum law.
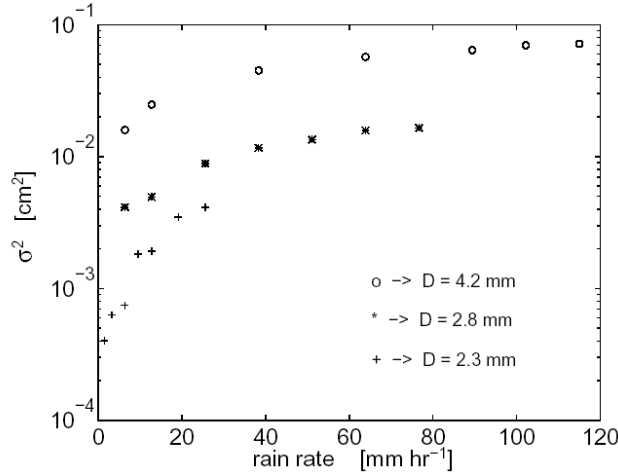

Fig. 2: Surface elevation variance obtained in the laboratory for different drop diameters.
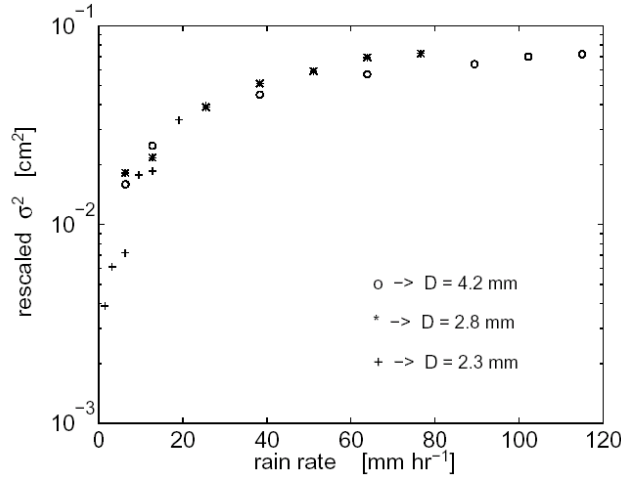

Fig.3. Surface elevation variance rescaled by the flux of squared drop momentum. From the 2.3 and 2.8 mm cases toward the (unchanged) 4.2mm case.

Knowing that only the largest drops will contribute to the surface energy associated with rain, we will, in a first stage, omit the dependence of fall velocity on the drop size. This simplification is justified by the fact that, for drops larger than 3 mm, the error introduced on the velocity is of a few percent only [6]. The dependence of velocity on drop size will be reintroduced in the next sections.

Hence, concentrating on the mass appearing in the square momentum law, we observe that the contribution of a drop to the surface energy is proportional to the sixth power of the drop diameter. Consequently, in the case of natural rain, the estimate of the surface elevation variance will strongly depend on the choice made for the drop size distribution (DSD).

In the following, we show that this difficulty can be overcome by directly linking the surface elevation variance with the reflectivity of the drops in the atmosphere. The reason is that, in the low-frequency approximation, the contribution of a drop is also proportional to the sixth power of the drop diameter [14]. In other terms, the reflectivity of the drops can be regarded as a good image of the perturbation they cause on the sea surface, and the relationship between these two quantities should be almost independent from the model chosen for the drop size distribution. In the following, we will illustrate this relationship by taking into account 18 different DSD's. In this exercise, we will assume the drops to be spherical, and the reflectivity data are produced from exact Mie computations, assuming lossy dielectric spheres. In the following, the models for the surface elevation variance and drop reflectivity will be recalled, and they will be confronted with each other.

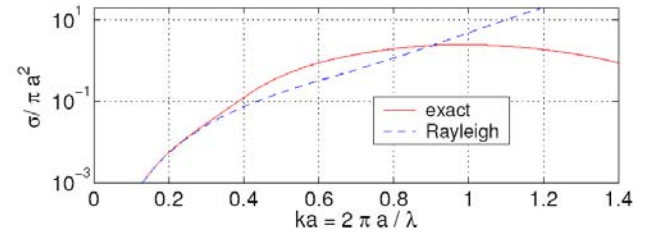## II. SURFACE ELEVATION VARIANCE AND RAINDROP REFLECTIVITY

Fig.4. Normalized radar cross-section of a spherical water drop at 13.8 GHz.

The energy contributed by a drop to the surface lasts for a certain time, which we will call the ``lifetime'' of the ring-waves τ_1. For natural rain, the surface elevation variance σ^2 is obtained by averaging the ring-wave energy over the drop size distribution $n(D)$. It yields:

$$\sigma^2 = \tau_1(R)\int_0^\infty a_1 D^6 v^2(D) v(D) n(D) dD \tag{1}$$

where a_1 is a constant, and the lifetime τ_1 is assumed to be depend on the rain rate R only. Its value depends on the interactions of ring-waves with each other, and with the other events resulting from drop impact (splashes, turbulence). For light rain rates, the lifetime is constant, because the interactions are negligible, while it tends to become smaller when the rain rate increases. $\tau_1(R)$ is obtained within a multiplicative constant from experimental data obtained with mono-disperse rain [3],[7].

The reflectivity from the drops in the atmosphere can be obtained using the Mie scattering theory. For drops that are very small compared to the wavelength (at least ten times smaller), the backscattering cross-section is proportional to

the sixth power of the drop diameter [10]. As explained above, this explains the functional similarity between the surface elevation variance and the atmospheric drop reflectivity.

$$Z = \int_0^\infty f(D)n(D)dD \qquad \text{with } f(D) \approx D^6 \qquad (2)$$

However, the condition referred to above, which stands for the Rayleigh scattering approximation, is not necessarily fulfilled at the frequencies used in existing satellite configurations. Hence, exact Mie computations [14] have been carried out here, assuming spherical drops. Fig. 2 shows the radar cross-section of a drop obtained versus drop diameter at 13.8 GHz, which is the frequency of the TRMM precipitation radar [10]. At that frequency, the drop complex dielectric constant is close to 36 - 35 j [13]. Obviously, the radar is sensitive to the very largest drops only.
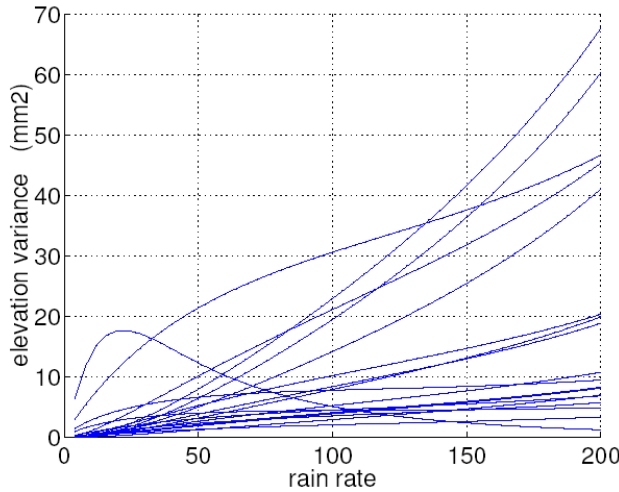

Fig.5. Surface elevation variance computed with the help of 18 different drop size distributions found in [10].

III. EFFECTS OF THE VARIABILITY OF DSD MODELS

The drop size distribution (DSD) models reported in the literature are widely deviating. In this paper, we selected 18 of the 22 distributions gathered by Montanari [11]. Four distributions have been discarded because of their poor rain-rate consistency. Using the notations defined above, the rain rate should be equal to:

$$R = 0.6 \cdot 10^{-3} \int_0^\infty n(D,R)D^3 v(D)dD \qquad (3)$$

Figs. 5 and 6 show the surface elevation variance and reflectivity factors obtained with the help of these DSD's. The uncertainty resulting from the choice of the DSD model is of the order of a 6:1 ratio. As it is not possible to say a priori which is the best DSD model (the actual DSD depends on many factors, like, for instance, the type of

clouds), it is very difficult to obtain an estimate of the surface energy induced by impacting drops. It should be noted that some DSD's lead to very high values of the elevation variance. This is due to the fact that many DSD's over-estimate the large-drop density.
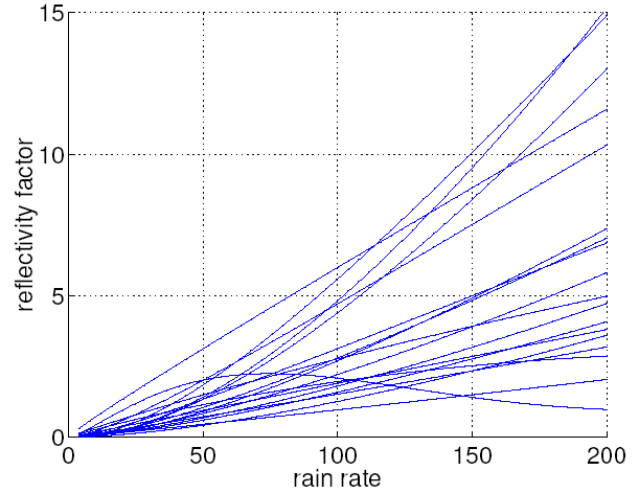

Fig.6. Reflectivity factor computed with the help of 18 different drop size distributions found in [11].

It is interesting to realize that the integral I appearing in the expression of the elevation variance (1) is similar to the one appearing in the reflectivity factor (2). Hence, those two quantities are almost proportional to each other. In other terms, the relationship between drop reflectivity and elevation variance presents a weak dependence on the actual model chosen for the DSD. This is visible in Fig. 7, where the dashed lines correspond to the use of a D^6
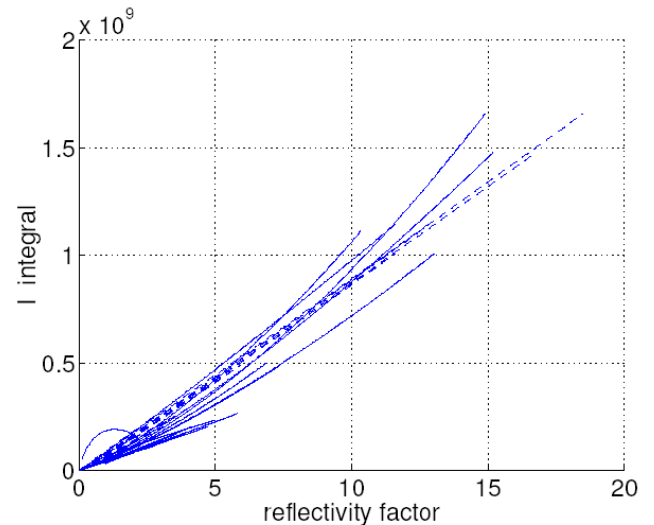

Fig 7. With the help of the same DSD models as before, I integral appearing in the expression of the surface elevation variance, versus the reflectivity factor. The dashed lines are obtained when the the Rayleigh approximation is used.

model for the drops cross-section, instead of the exact Mie computations. Obviously, when the surface elevation variance is obtained from reflectivity data, the choice of the DSD model becomes a much less critical question.

Fig. 7 only shows the value of the integral appearing in the expression of the surface elevation variance. For completeness, the lifetime function should also be estimated. We assumed that it depends only on the rain rate. In most cases, there is no independent data available on the rain rate, such that it has to be delineated from the drop reflectivity. As the rain rate (3) and the drop reflectivity (2) do not have similar drop-size dependences, the estimated rain rate will be strongly dependent on the choice of the DSD. This constitutes the standard challenge of rain rate estimation. However, it should be recalled that the lifetime τ has a weak dependence on the rain rate. Hence, the presence of the lifetime in the expression of the surface elevation does not dramatically enhance the dependence of the result on the DSD. This is shown in Fig. 8.
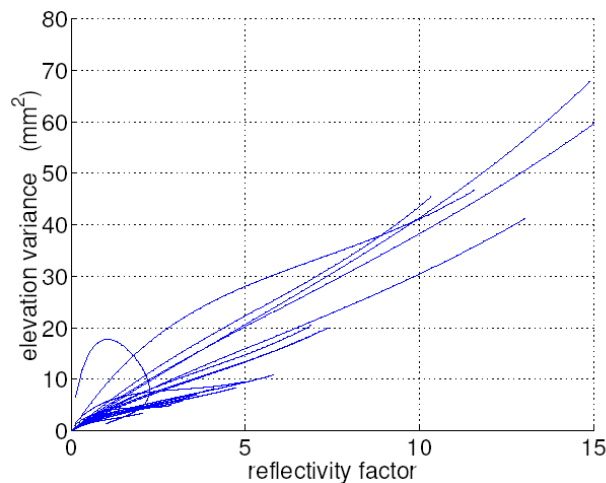

Fig.8. With the help of the same DSD models as before, surface elevation variance versus reflectivity factor.

IV. CONCLUSION

Rain can strongly affect the reflectivity from the surface of the sea. The effect of the impacting drops on the surface roughness increases very fast with drop size. As a result, only the largest drops affect the surface roughness. This effect is very difficult to estimate when only the rain rate is known, because the large drop content strongly depends on the models chosen for the DSD (cf. Fig. 5). This uncertainty can be dramatically reduced when drop reflectivity data are available, as it is the case for the TRMM data. Indeed, drop reflectivity and surface elevation variance correspond to almost identical moments of the DSD. This is illustrated in Fig. 8, where we see that the about 6:1 uncertainty is now reduced to about 2:1. The remaining uncertainty is caused by (i) the departure of the Mie solution from the Rayleigh approximation at high

frequencies and (ii), the dependence on the surface elevation on the lifetimes of the ring-waves. The latter quantity certainly deserves further attention.

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